ANNUAL REPORT

Joint Services Electronics Program
Contract DAAL-03-87-K-0059
January 1, 1988 - December 31, 1988

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TWO-DIMENSIONAL SIGNAL PROCESSING AND STORAGE
AND
THEORY AND APPLICATIONS OF ELECTROMAGNETIC MEASUREMENTS

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January 1, 1989

GEORGIA INSTITUTE OF TECHNOLOGY
A UNIT OF THE UNIVERSITY SYSTEM OF GEORGIA
SCHOOL OF ELECTRICAL ENGINEERING
ATLANTA, GEORGIA 30332

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Georgia Institute of Technology
School of Electrical Engineering
Atlanta, Georgia 30332

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19. ABSTRACT (Continue on reverse if necessary and identify by block number)

This is an annual report on research conducted under the auspices of the Joint Services Electronics Program. Specific topics covered are: digital signal processing, parallel processing architectures, two-dimensional optical storage and processing, hybrid optical/digital signal processing, electromagnetic measurements in the time domain, and automatic radiation measurements for near-field and far-field transformations.

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Contents

1 Overview

This annual report covers the second year of research carried out under Contract DAAL-03-87-K00059. The research is part of the Joint Services Electronics Program and is administered by the U. S. Army Research Office. Research activities in this program are concentrated in the areas, (1) Two-Dimensional Signal Processing and (2) Theory and Application of Electromagnetic Measurements.

The research in two-dimensional signal processing is carried out in six work units. These work units are complementary, and research activities interact and reinforce one another in many ways. Research in Work Unit One, *Iterative Signal Restoration and Estimation*, and Work Unit Two, *Representation, Coding, and Analysis of Images*, is concerned with the theory, design, and implementation of multidimensional digital signal representations and digital signal processing algorithms and systems. Work Unit Number Three, *Multiprocessor Architectures for Digital Signal Processing*, focuses on hardware and software problems in the use of multiple processors for high-speed implementations of digital signal processing algorithms. The research in Work Unit Four, *Two-Dimensional Optical Information Processing*, is concerned with theoretical and experimental aspects of two-dimensional optical information processing. Work Unit Five, *Two-Dimensional Optical/Electronic Signal Processing*, is concerned with the theory, implementation, and application of hybrid optical/electronic methods for high throughput signal processing. Work Unit Eight, *Angular Spectrum Analysis for Non-Uniform Arrays*, seeks to develop new angle-of-arrival estimation techniques that are not restricted to uniform arrays of sensors.

The other two work units in the JSEP program are concerned with electromagnetic measurements. In Work Unit Six, *Electromagnetic Measurements in the Time- and Frequency-Domains*, research is concerned with the development of new methodology for making electromagnetic measurements directly in the time domain or over a wide bandwidth in the frequency domain. Work Unit Seven, *Automated Radiation Measurements for Near- and Far-Field Transformations*, is concerned with developing an understanding of the near-field and far-field coupling between antennas in the presence of scatterers.

The report begins with a summary of the most significant accomplishments (in the judgment of the lab directors) during the period January 1, 1988 to December 31, 1988. Following this are brief reports on the individual work units. These reports list personnel supported and discuss in general terms the research that was carried out during the reporting period. Also included in each work unit report is a complete list of publications on the research during this period. These publications are reprinted in the Annual Report Appendix, which is available in micro-fiche form as a separate document.

2 Significant Research Accomplishments

The following accomplishments are, in the judgment of the laboratory directors, of particular significance and potential and are therefore worthy of special mention.

2.1 Electron Wave Optics in Semiconductors

Starting from fundamental principles, quantitative analogies between quantum mechanical electron waves in semiconductor materials and electromagnetic optical waves in dielectrics have been developed. These analogies make it possible to apply much of the already existing electromagnetic theory and design methodology directly to the development of many new classes of electron wave optical devices such as narrow-band superlattice interference filters. Possible new electron wave devices include low pass filters, high pass filters, notch filters (narrow band and wide band), bandpass filters (narrow band and wide band), and impedance transformers (antireflection coatings), and high reflectance surfaces (dielectric mirrors). These electron wave filter devices can have Butterworth (maximally flat), Chebyshev, elliptic function, or other type of characteristics. Narrow band filters can be incorporated monolithically into transistor structures in order to increase their speed. Pumping a superlattice resonant cavity gives rise to the possibility of a coherent electron wave amplifier and/or emitter. These are all one-dimensional quantum well type devices. Two-dimensional and three-dimensional devices such as beamsplitters, cylindrical lenses, spherical lenses, and diffraction gratings ar also possible using quantum wire and quantum box structures. These devices could assist in the control of freespace electron beams in fields such as electron spectroscopy, electron beam lithography, and electron diffraction analysis of crystals.

2.2 Optimal Constraint-Based Signal Restoration

It has been shown that problems in signal restoration or estimation can be considered to be convex programming problems. This approach has led to the development of new algorithms for the optimal restoration of signals that have been distorted by a linear operator and corrupted by noise. The resulting algorithms can incorporate prior knowledge of the signal in the form of bounds and prior knowledge of the noise in the form of power levels and the power density spectrum. A variety of cost criteria such as least squares, maximum entropy, and minimum cross entropy cost criteria can be applied, leading to algorithms whose performance criteria can be adapted to different classes of signals and distortions. Also, the maximum entropy and minimum cross entropy criteria have been modified to accommodate prior estimates of the unknown signal, thereby making them more reliable estimators for general signal restoration problems.

2.3 Radome Anomaly Detection Using Spherical Near-Field Measurement

A theory and technique have been developed, implemented and tested for the non-invasive, high accuracy determination of radome wall performance. The technique, which involves the backward propagation of the measured spherical surface fields surrounding the radome, has a demonstrated spatial resolution of better than one-half wavelength. The demonstrated high accuracy and resolution of the technique could lead to an order of magnitude improvement in radome electromagnetic performance.

Work Unit One

TITLE: Iterative Signal Restoration and Estimation

SENIOR PRINCIPAL INVESTIGATORS:

Russell M. Mersereau, Regents' Professor and Rockwell Fellow
Monson H. Hayes, Associate Professor

SCIENTIFIC PERSONNEL:

C. Auyeung, (Ph.D. received, December 1988)
S. J. Reeves, (Ph.D. Candidate)

SCIENTIFIC OBJECTIVE:

The objective of this research is to study and develop a broad class of iterative signal restoration techniques to remove linear and non-linear degradations from signals through a knowledge of the distortion operator and the class of allowable signal. This work brings together ideas from signal processing, functional analysis, optimization theory, statistical filtering, and signal modeling.

RESEARCH ACCOMPLISHMENTS:

- *Constrained Signal Restoration*

  This has been a continuing area of research. During this period a major tutorial paper was completed describing results on constrained image deblurring, a doctoral thesis was completed on the general problem of signal restoration, and research was begun on the problem of blind deconvolution by a relatively new doctoral student. The latter two topics are described below.

- *Optimal Constraint-Based Signal Restoration*

  The thesis by Auyeung looked at the problem of signal restoration (estimation) as a convex programming problem. It had several components. One of these was the formal development of algorithms for the optimal restoration of signals which have been distorted by a linear operator and corrupted by noise. These procedures incorporate prior knowledge of the signal in the form of bounds and prior knowledge of the noise, in the form of power levels and the power density spectrum. Least squares cost criteria, maximum entropy cost criteria, and minimum cross entropy cost criteria were considered. The least squares criterion produced the most satisfactory restoration when the underlying distribution was smooth, but

the maximum entropy criterion was a better choice when the underlying distribution was impulsive, as might be the case in trying to resolve images of closely spaced bright objects, such as stars or missile firings.

Another result from Auyeung's thesis concerned the development of efficient algorithms for performing least-squares restorations when the distortion operator is zero phase – a reasonable assumption for motion blur, out-of-focus blur, and certain forms of atmospheric turbulence. The restoration can be performed in this case by solving several sets of Toeplitz or block Toeplitz linear equations.

A final result from this thesis suggested modifications to the maximum entropy and minimum cross entropy cost criteria that may make them into more reliable estimators for general signal restoration problems. These modifications allow these estimators to accommodate prior estimates of the unknown signal.

- *Blind Image Deblurring*

  An important limitation of virtually all image restoration schemes is that they require knowledge of the underlying distortion, a condition which is difficult to achieve in practice. This newly initiated study is considering the problem of blur removal when the blur is incompletely known. For such a scheme to work, prior knowledge of the class of feasible solutions and of the class of feasible blurs is essential. Our initial approaches to this problem have focused on techniques for blur estimation.

- *The Phase Retrieval Problem*

  This work is concerned with the recovery of an image from knowledge of its Fourier transform magnitude (intensity). The problem that is being studied builds upon some earlier JSEP research by A. Katsaggelos which was concerned with the reconstruction of linearly distorted images from more than one blurred observation. Specifically, we are investigating a new approach for phase retrieval which is based on multiple observations of Fourier intensity information. It is well known, for example, that an image can be easily recovered from its Fourier intensity if the original image contains a latent reference point [1-3]. Therefore, we have modified this latent reference point condition by considering the problem of image recovery given the Fourier intensity of the image and the Fourier intensity of a image that has a latent reference point added to it. Specifically, given the Fourier intensity of an image $x(m,n)$ and the Fourier intensity of a modified image,

$$y(m,n) = x(m,n) + A\delta(m - m_0, n - n_0)$$

  we have shown that with very modest constraints, the image may be easily and uniquely recovered by simply solving a set of linear equations. Unlike the latent reference point condition, however, the superimposed point source is contained within the support of the image.

This condition was then generalized by replacing the single point source $A\delta(m - m_0, n - n_0)$ with a superposition of point sources. Specifically, given the Fourier intensity of $x(m,n)$ and the Fourier intensity of

$$y(m,n) = x(m,n) + \sum_{k}^{N} A_k \delta(m - m_k, n - n_k)$$

some general conditions for the unique reconstruction of $x(m,n)$ have been developed [4].

The ultimate goal of this research is to determine a general set of conditions for which an image $x(m,n)$ may be uniquely reconstructed from the intensity of its Fourier transform and the Fourier intensity of an image $y(m,n) = L[x(m,n)]$ that is related to $x(m,n)$ by some known transformation.

- *Digital Filter Design*

This work re-examined the design of FIR digital filters using windows. Attention was focused not on the choice of the window, but on the choice of the ideal response. We showed that nearly equiripple designs could be obtained using Kaiser windows by properly choosing the ideal response in the transition bands. Design curves were developed to assist in the selection of the free parameters associated with the method. The technique is simple and it works well for both one and two-dimensional FIR filters, although we did not succeed in producing useful design curves for the two-dimensional case.

The design of one-dimensional digital filters does not lie within the research thrust of this JSEP research program, but inspiration does not always come on cue, and not always in prescribed areas. The majority of this work was done by people not supported by JSEP and the resulting technique was described in two conference presentations.

PUBLICATIONS:

Ph.D. Theses:

1. C. Auyeung, *Optimal Constraint-based Signal Restoration and its Applications*, Ph.D. Thesis, September 1988.

Journal Articles:

1. R. M. Mersereau, Z. Shen and M. H. Hayes, "Selection of Ideal Filters for the Window Design Method," *Signal Processing IV*, (Lacoume et al, editors), North Holland, 1988.

2. P. M. Carrion, C. Auyeung and R. M. Mersereau, "A New Approach to Constrained Seismic Travel-Time Tomography," submitted to *Geophysics*.

3. R. M. Mersereau, Z. Shen, and M. H. Hayes, "Effect of Ideal Transition Specification on Window Designs," *IEEE ASSP Digital Signal Processing Workshop*, September 1988.

4. R. L. Lagendijk, J. Biemond and R. M. Mersereau, "Iterative Methods for Image Deblurring," submitted to *IEEE Proceedings*.

Conference Proceedings:

1. C. S. Kim, J. Bruder, M. J. T. Smith and R. M. Mersereau;, "Subband Coding of Color Images Using Finite State Vector Quantization," *International Conference on Acoustics, Speech and Signal Processing*, pp. 753-756, New York, 1988.

2. C. Auyeung and R. M. Mersereau, "The Dual Approach to Signal Restoration," submitted to *International Conference on Acoustics, Speech and Signal Processing 1989*.

3. C. Auyeung and R. M. Mersereau, "On Selecting a Cost Functional for Optimal Signal Restoration," submitted to *International Conference on Acoustics, Speech and Signal Processing 1989*.

4. C. Auyeung and R. M. Mersereau, "Efficient Algorithms for Least Squares Restoration," submitted to *International Conference on Acoustics, Speech and Signal Processing 1989*.

Work Unit Two

TITLE: Representation, Coding, and Analysis of Images

SENIOR PRINCIPAL INVESTIGATORS:

R. W. Schafer, Regents' Professor
R. M. Mersereau, Regents' Professor and Rockwell Fellow

SCIENTIFIC PERSONNEL:

F. J. Malassenet, (Ph.D. Candidate)
L. Hertz, (Ph.D. Candidate)
C. H. Richardson, (Ph.D. Candidate)

SCIENTIFIC OBJECTIVE:

The first major objective of this work unit is to study and develop new approaches to the modeling of images and to the representation of the information contained in images. A second major objective is to use such models and representations to solve problems in automatic extraction of information from images and in efficient digital coding of images.

RESEARCH ACCOMPLISHMENTS:

- *Thresholding for Image Analysis*

  - *Multi-level thresholding*
    Thresholding is an effective method for simplifying images while retaining shape and geometrical structure. Multiple thresholds are needed when thresholding images containing several objects of differing brightness or reflectivity. Also, to account for variations of grey levels due to non-uniform illumination, it is often necessary to allow the thresholds to vary across the image. A technique called *edge matching* has been developed for the class of images consisting of untextured objects on a untextured background. The multiple thresholds are adjusted so that the edges of the thresholded image closely match the edges of the original grey-tone image. The result is a multi-level thresholded image that preserves the shape and geometrical structure of the objects in the image. It can then be "sliced" to extract objects that occupy the different threshold bands. Morphological systems can then be used to process these slices.

This work has been described in a paper entitled "Multi-level Thresholding Using Edge Matching" to be published in *Computer Vision, Graphics and Image Processing.* Additional work is continuing on enhancements to this technique to include images with textured objects.

- *Thresholding Greytone Edge Maps*
  Many edge-detection algorithms exist which yield good, grey-scale edge image. In a large number of applications, it is necessary to threshold this edge image into a binary image. Since the edges appear in the greytone edge map as peaks of varying magnitudes, it is more of a peak picking problem rather than a thresholding problem. A simple method using the morphological top hat transformation to accomplish this peak picking has been developed. By choosing a structuring element of the appropriate size, the resultant edges may have any desired width. This method may generalize to other one and two dimensional peak picking applications.

- *Automated Image Analysis*

  In many image analysis problems, considerable *a priori* knowledge is available about the image under test. This is the case in many problems in computer vision, automated inspection, surveillance and automatic target tracking. Often the information is in symbolic form. Interesting problems arise in combining the symbolic information with the numeric representation of a digitized image. This is particularly true when the field of view is more restricted than the symbolic representation and it is necessary to determine which part of the object or scene is in view.

  Investigations of problems of this sort have been continued with encouraging success. Specifically, PC boards represented in the Cal Tech Intermediate Format (CIF) have been fabricated and subsequently imaged. Techniques have been developed that successfully extract a CIF-like representation of the image. This information has been incorporated into a graph. A similar graph can be constructed from the symbolic representation. Extracting the connectivity information from both graphs allows for comparison. Techniques have been developed to determine all possible locations of an image consisting of only a square section of the board.

  This work has obvious applications in automated visual inspection of electronic circuits and it may generalize to other types of problems where a map of physical features may be available to compare to images of the region covered by the map.

- *An Environment for Morphological Signal Processing*

  This research has focused on the development of a LISP-based signal processing environment for the representation of discrete-time signals for both symbolic and numeric manipulations of morphological expressions. Numerical manipulations are facilitated by a signal representation based on the notion of *signal classes* and

abstract data objects. Signals are organized into signal classes in order to allow the possibility of inheritance of computational methods and other signal properties.

Symbolic manipulations are performed by applying classes of morphological rules to compound morphological expressions. Currently the symbolic manipulations are performed in an expert system manner with a forward chaining control strategy for generating both both simplifications and equivalent forms of expressions.

- *Knowledge-Based Analysis of 4-D Images*

  This research has focused on the knowledge-driven detection and identification of moving edges in time varying 3-D imagery. The specific context is the analysis of cardiac nuclear magnetic resonance images but the techniques are applicable to other problems. The Dempster-Shafer theory of evidence is used to label line segments that have been found by low level signal processing, to fill in gaps, and resolve structural ambiguities. Knowledge is entered through a number of conditional probabilities derived from hand labeled training data. Most of the support for this effort is from non-JSEP sources.

- *Basis Representation of Morphological Systems*

  This research is directed towards providing insight into the determination of the basis of morphological transformations. In previous JSEP-supported research by Maragos, it was shown that any transformation which is translation invariant, increasing, and upper semi-continuous can be represented as a union of erosions by elements of its basis. This theorem, although of great importance, offers little or no insight into how the basis may be analytically determined from an arbitrary transformation, or whether it has a finite number of elements (a necessity for a practical implementation). Methods for determining the basis as well as additional constraints imposed on the transformation required for these methods are being investigated. As an example, the basis of the intersection of an arbitrary (finite) number of set dilations is given by the minimum (with respect to set inclusion) union of elements of the individual dilation basis elements. Since the dilation basis is finite (in a digital setting) if the structuring element is compact, the intersection of dilations leads also to a finite basis.

  This work represents a first step toward a design methodology for morphological systems. Results will be incorporated into the above mentioned environment for morphological signal processing.

- *Texture Modeling*

  This research is concerned with the representation of natural textures by deterministic fractal models. More traditional approaches to the texture modeling problem treat a texture as a stationary random field. Fractal models represent a potentially very efficient alternative representation since they can be reconstructed

from relatively few parameters using iterated affine transformations. Fractal representations are quite different from traditional ones, however, since they force the image to be viewed as a finite resolution rendition of a measure, rather than as a function.

The work to date has been preliminary and no breakthroughs have occurred. A software environment has been created which permits textures to be synthesized from the affine parameters, and which permits images of natural textures to be manipulated. A number of preliminary approaches to the inverse problem of determining which affine parameters best render a particular natural texture have been tried, but the results have been mixed.

PUBLICATIONS:

Journal Articles:

1. L. Hertz and R. W. Schafer, "Multilevel Thresholding using Edge Matching," *Computer Vision, Graphics and Image Processing*, vol 44, pp. 279-295, 1988.

2. L. Hertz and R. W. Schafer, "On Thresholding Edge Images," submitted to *Computer Vision.*

DoD INTERACTION:

R. W. Schafer and C. H. Richardson participated as speakers in the *Workshop on Mathematical Morphology*, sponsored by ARO and MICOM and held at the Tom Bevill Center in Huntsville, AL, July 25-26, 1988. Also participating was Professor P. Maragos of Harvard University who was supported by JSEP while a doctoral student at Georgia Tech. The purpose of the workshop was to acquaint MICOM and NASA personnel with the fundamentals and potential applications of morphological systems.

Work Unit Three

TITLE: Multiprocessor Architectures for Digital Signal Processing

SENIOR PRINCIPAL INVESTIGATORS:

T. P. Barnwell, III, Professor and Rockwell Fellow
D. A. Schwartz, Assistant Professor

SCIENTIFIC PERSONNEL:

A. Massumi, (Project Student and Ph.D. Candidate)
H. R. Forren, (Graduate Research Assistant and Ph.D. Candidate)
P. R. Gelabert, (Graduate Research Assistant and Ph.D. Candidate)
L. P. Heck, (Graduate Research Assistant and Ph.D. Candidate)
C. P. Hong, (Graduate Research Assistant and Ph.D. Candidate)
B. M. Kim, (Graduate Research Assistant and Ph.D. Candidate)
D. J. Pepper, (Graduate Research Assistant and Ph.D. Candidate)
S. A. Spalding, (Graduate Research Assistant)
K. K. Truong, (Graduate Research Assistant and Ph.D. Candidate)

SCIENTIFIC OBJECTIVE:

The primary objective of this work unit is to develop systematic techniques for the automatic generation of provably optimal multiprocessor implementations for a broad class digital signal processing (DSP) algorithms and for a broad class of multiprocessors systems. Stated in another fashion, the goal of this research is to develop DSP "compilers," where the input is an algorithm specification and the output is a complete, optimal multiprocessor implementation. An additional long-term goal is to make these optimal multiprocessor compilers available to a broad class of DSP system designers.

A basic philosophy of this research has always been to perform the theoretical developments in the context of an actual multiprocessor system. The first system used for this purpose, an eight processor LSI-11/2 system, is now obsolete. The current research is being tested using the OSCAR-32, a personal computer (PC) based multiprocessor utilizing the AT&T DSP-32 floating point DSP microprocessor [3].

RESEARCH ACCOMPLISHMENTS:

Work on the area of multiprocessor architectures for DSP has been centered in five areas: periodic scheduling theory; scheduling theory for parallel pipeline architectures; loop unwrapping for scheduling cyclic graphs; optimal scheduling of graphs with data dependent branching; the development of the OSCAR-32 multiprocessor; and a graph

compiler for commercial DSP chip based multiprocessors. In addition, a number of smaller miscellaneous projects have been accomplished.

- *Periodic Scheduling Theory*

  Work performed by Helmut Forren [5] has resulted in important generalizations and unifications of prior periodic scheduling methods. In prior work at Georgia Tech, three optimal periodic scheduling methods had been developed: SSIMD, cyclo-static and MCIMD [5]. MCIMD (*Multi-Cyclic Instruction Multiple Data* is an extension of cyclo-static schedules based primarily on the use of heterogeneous processing elements.

  Recent work has resulted in the unification of SSIMD, cyclo-static and MCIMD as well as the more traditional scheduling methods of CPM[1],ASAP/ALAP[2], systolic array schedules and static pipeline schedules [1]. All of these schedules can be represented in a single unified form based on a *period matrix* and a *cycling vector*. Furthermore, any of the schedule types can be formally transformed into a generalized SSIMD[3] schedule, while a static schedule can be transformed into any of the other classes of schedules. Such transforms can be used to classify all deterministic parallel schedules into equivalence classes.

  The importance of this unification was that it showed that the generalized SSIMD schedule was the optimal class for homogeneous processors and that generalized *parallel SSIMD* (PSSIMD) was the optimal class for heterogeneous processors. Furthermore it provided a powerful conceptual framework that led to a simplified representation of schedules and a corresponding simplification of the scheduling algorithm. Based on this result, a preliminary, general purpose, parallel processing architecture based on a low order chorded ring has been proposed.

  Other related work was the continued extension of performance bounds for multiprocessors. This included a new method to determine the true, achievable, minimum processor bound (for a given processing rate), as well as a causal throughput delay bound.

- *Scheduling Theory for Parallel Pipeline Architectures*

  A new research topic which was initiated last year was the extension of cyclic multiprocessor scheduling techniques such as those used in the cyclo-static and generalized SSIMD compilers to pipeline and parallel pipeline architectures. This new theory is based on a set of transformations which represent pipeline and parallel pipeline architectures as parallel MIMD systems. These transformations represent individual pipeline processors (such as the AT&T DSP32 processor used in the OSCAR-32) as a number of *pseudo-processors* in a parallel structure. After

[1] Critical Path Method.

[2] As Soon/Late As Possible.

[3] For the case of homogeneous processors.

the transformations, the result is a fully parallel architecture with no pipelined elements. Thus, parallel processor scheduling techniques can be applied directly to the transformed architectures to achieve optimal or near-optimal schedules. These multiprocessor realizations are then transformed back into their equivalent optimal or near optimal pipeline or parallel pipeline realization.

The multiprocessor representation needed to accommodate the transformed pipeline and parallel pipeline systems is nearly identical to that needed for parallel systems. The one difference is that the extended representation must allow for a synchronous clock skew between (groups of) individual processors. The leads to the concept of *clock classes*, which are the sets of all processors which share the same clock skew. In a traditional multiprocessor system, the clock skew is zero and all the processors belong to the same clock class. The effect of the clock classes is to provide a new set of constraints which are applied during the pruned tree search used in the cyclic scheduling algorithms.

At this point in time, an initial compiler has been written for finding the optimum pipelined implementation for a single pipelined processor in which the number of pipelined stages is equal to the processor bound of the graph. The eventual goal is to write a compiler for general architectures in which there are a large number of identical pipelined processors.

- *Loop Unrolling for Code Generation* vs *Cyclo-Static Scheduling*

  Prior work by S. H. Lee examined the issue of SSIMD schedules based on imperative program specifications. With the development of commercial VLIW computers, the question of the applicability of cyclo-static scheduling to code generation for scientific applications was investigated. Scientific code can often be characterized by nested "DO" loops containing a number of arithmetic assignment statements[4]. When the number of iterations of the loop is large they can be conceptually approximated as infinite loops, thus making them amenable to the optimal cyclo-static scheduling technique for recursive flow graphs.

  A preliminary investigation into these issues [4] showed that more traditional techniques of code generation for commercial supercomputers and mini-supercomputers is based on representing the "DO" loop as a directed acyclic graph (DAG) based on one iteration, or a few iterations in the case of the "advanced" technique of loop unrolling. The scheduling of the resulting DAG is fundamentally related to CPM methods. The representation of the loop as an acyclic graph of finite extent destroys inherent parallelism. A limited number of simple cases were investigated which showed a significant performance advantage of the cyclic scheduling approach of cyclo-static scheduling.

[4] Closely related work based on analyzing the "Lawrence Livermore Loops" can be found in [2].

- *Optimal Scheduling of Graphs with Data Dependent Branching*

  Most of the previous research in this work unit has assumed that the DSP algorithm of interest can be represented as a cyclic graph. This assumption precludes all algorithms in which data dependent branching occurs. The goal of this research is to extend the existing multiprocessor scheduling theory to include algorithms with small amounts of data dependent branching.

  The approach in this area is to combine recent techniques developed for scheduling very wide instruction word machines (VLIW) with data dependent branching with our own techniques for scheduling fully specifiedflow graphs in order to develop a compiler which can find optimal or near-optimal schedules for graphs with data dependencies. The first goal is to solve the problem for graphs with only one data dependency.

  This work is just now beginning. At this point, the emphasis is on developing an extended formalism which extends our previous concepts of optimality to graphs with data dependencies. The data dependencies include both deterministic dependencies and stochastic dependencies.

- *Development of the OSCAR-32*

  The OSCAR-32 synchronous multiprocessor system is the current target system for the multiprocessor research. It is hosted on personal computers, and is composed of processing elements designed and constructed at Georgia Tech. Several small OSCAR-32 systems have been configured (up to three boards and nine processors). In 1988, considerable progress was made toward the construction of a much larger OSCAR-32 system.

  Figure 1 shows a block diagram of an OSCAR-32 constituent processor. This processor board contains three AT&T WE-DSP32 processing chips which can deliver up to 37.5 MFLOPS. This board was designed in 1986 and 1987, and was extensively tested in small multiprocessor systems in late 1987 and early 1988. In late 1988, twenty constituent processors were constructed and tested.

  In 1989, a sixteen processor system will be constructed as shown in Figure 2. In order to accomplish the communications, three outside "communications motherboards" -such as the one shown in Figure 3 must be constructed and tested. At the current time, two such boards have been completed and the third is under construction.

- *DSP Chip Architecture for Multiprocessing*

  While single chip DSP processors are approaching a significant level of maturity, they are not well designed to met the need of multiprocessing,particularly with respect to fine grain multiprocessing. Based on the WE DSP32 floating point DSP chip a small multiprocessor, the OSCAR-32, was implemented. The scheduling methodology discussed above applies to any synchronous, data independent

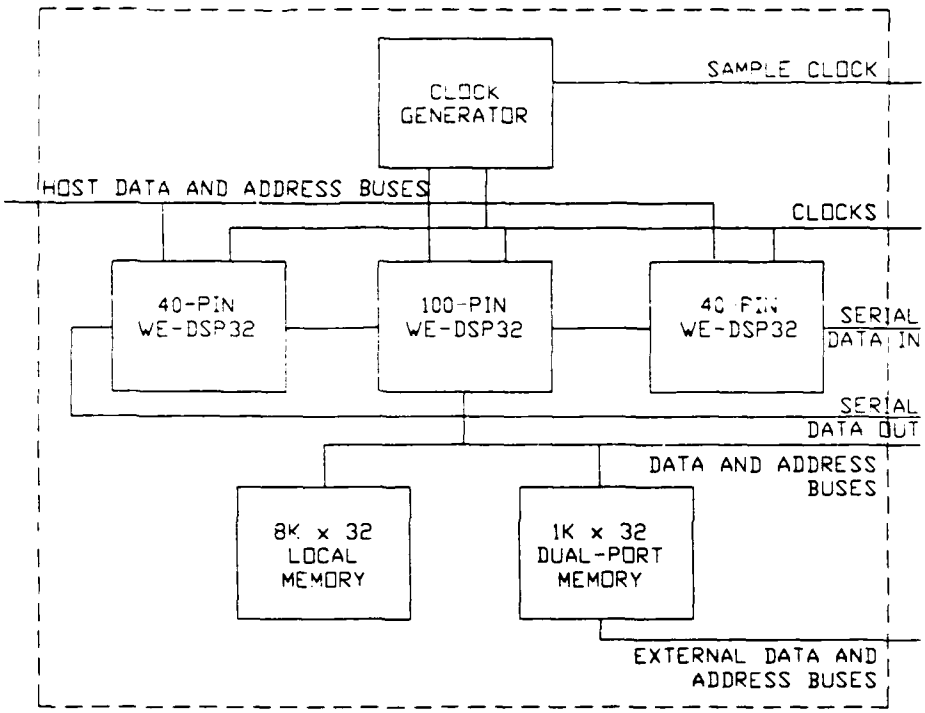

Figure 1: Block diagram of the OSCAR-32 constituent processor board

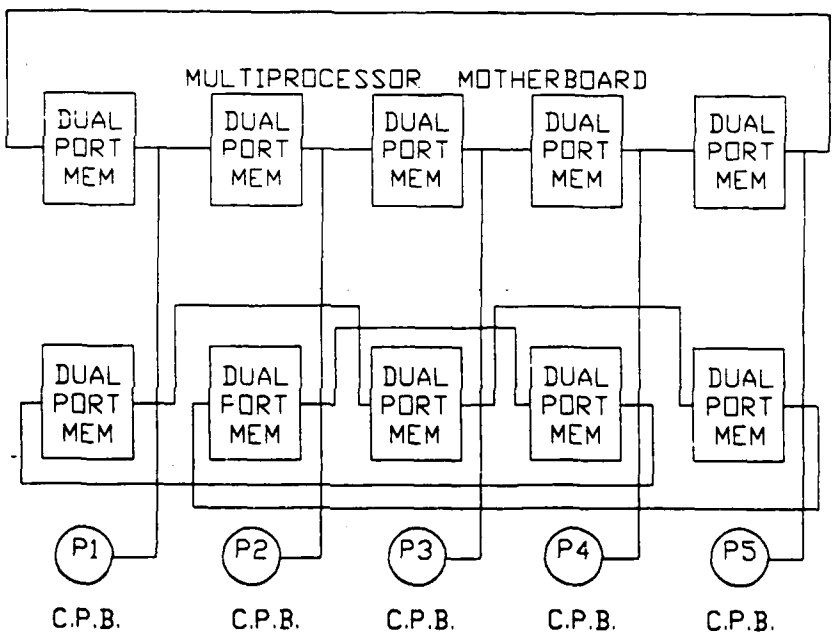

Figure 2: Block diagram of the OSCAR-32 5-processor fully interconnected system

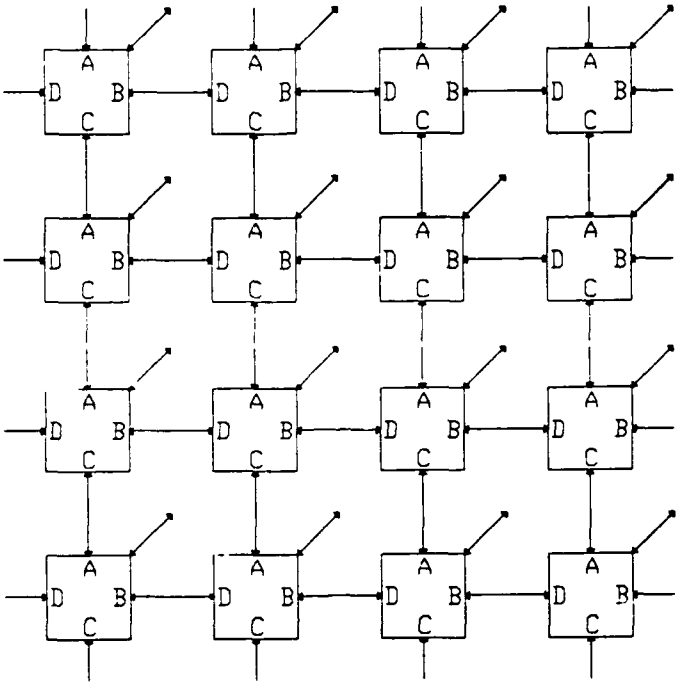

Figure 3: Block diagram of the sixteen processor OSCAR-32 system

system, however it may not be computationally tractable without further architecture constraints. The OSCAR-32 has several features that make it difficult to practically apply the (P)SSIMD scheduling methodology. A practical graph based compiler for the system is under development. The compiler extends well know code generation techniques and combines them with extensions to list based CPM scheduling. The main goal is to determine what are the bottlenecks in the architecture in terms of a realization and in terms of a practical compiler. A preliminary version is currently functioning and produces good code for the OSCAR-32 multiprocessor. Work is now under way to further expand and improve the functionality of the compiler and to systematically explore a set of architectural choices with the goal being a practical single chip DSP for fine grain multiprocessing with practical compiler/scheduling tools.

- *Miscellaneous Projects*

  In addition a number of limited projects were undertaken during this time period. Most of these involved supervising graduate students who were not supported by this contract. In support of the development of the OSCAR-32, initial efforts in support tools were undertaken. This included portions of a debugger (in conjunction with L. Heck, research assistant) and a simulator (in conjunction with S. Spalding, research assistant). A preliminary investigation of the applicability of

processor bounds and cyclo-static schedules to the implementation of neural net algorithms was conducted (in conjunction with K. Truong, research assistant). An initial study of a design assistant for algorithm development for multiprocessors resulted in research into optimal special case FFT code generation (performed in conjunction with L. Heck, research assistant). Finally, two software simulations of multiprocessor systems based on the Motorola 56000 DSP chip were completed. In both cases, the simulated multiprocessor were used to realize SSIMD implementations of digital filters.

References:

1. H.F. Forren and D.A. Schwartz, "Transforming Periodic Synchronous Multiprocessor Programs," *Proc. of the International Conference on Acoustics, Speech and Signal Processing*, Dallas, TX, April, 1987.

2. K. Hwang, "Pipeline Nets," *Proc. of the IEEE*, Jan., 1988.

3. S.J.A. McGrath, T.P. Barnwell III and D.A. Schwartz, "A WE-DSP-32 Based, Low Cost Multiprocessors for Cyclo-Static Implementations," *Proc. of the International Conference on Acoustics, Speech and Signal Processing*, Dallas, TX, April, 1987.

4. D.A. Schwartz, "Cyclo-Static Realizations, Loop Unrolling and CPM: Optimal Multiprocessor Scheduling," *Published by Plenum Publishing in 1988 as Chapter 16 in a book edited by Stuart Tewksbury* (based on an invited presentation at the 1987 Princeton Workshop on Algorithm, Architecture and Technology Issues in Models of Concurrent Computations, Sept. 1987, Princeton, NJ), Chapter 16.

5. H.R. Forren, "Multiprocessor Design Methodology for Real Time Digital Signal Processing Systems Represented by Shift Invariant Flow Graphs" Ph.D. Thesis, Georgia Institute of Technology, Atlanta, Georgia, May, 1988.

PUBLICATIONS:

Ph.D. Theses:

1. H. R. Forren, "Multiprocessor Design Methodology for Real Time Digital Signal Processing Systems Represented by Shift Invariant Flow Graphs" Ph.D. Thesis, Georgia Institute of Technology, Atlanta, Georgia, May, 1988.

Books and Journal Articles:

1. D. J. Pepper, T. P. Barnwell III and M. A. Clements, "A Ring Parallel Processor for Hidden Markov Model Training," accepted for publication in *IEEE Transactions on ASSP.*

2. D. A. Schwartz, "Cyclo-Static Realizations, Loop Unrolling and CPM: Optimal Multiprocessor Scheduling," *Concurrent Computations (Algorithms, Architecture and Technology*, Chapter 16, Published by Plenum Press, New York, 1988. Articles published based on an invited presentation at the 1987 Princeton Workshop on Algorithm, Architecture and Technology Issues for Models of Concurrent Computation, September 30-October 1, 1987, Princeton University, Princeton, New Jersey.

Papers in Conference Proceedings:

1. S. H. Lee and T. P. Barnwell III, "Optimal Multiprocessor Implementations from Non-Parallel Algorithm Specifications," *1988 International Conference on Acoustics, Speech, and Signal Processing*, New York, NY, April, 1988.

Work Unit Four

TITLE: Two-Dimensional Optical Storage and Processing

SENIOR PRINCIPAL INVESTIGATORS:

Thomas K. Gaylord, Regents' Professor
E. I. Verriest, Associate Professor
J. A. Buck, Assistant Professor

SCIENTIFIC PERSONNEL:

T. J. Drabik, Graduate Research Assistant (Ph.D. Candidate)
M. C. Fazio, Graduate Research Assistant (Ph.D. Candidate)
T. A. Maldonado, A. R. O. Fellow (Ph.D. Candidate)

SCIENTIFIC OBJECTIVE:

The long-term objective of this research is to develop broadly-based, theoretical and experimental knowledge of two-dimensional optical information processing including algorithms, architectures, systems, and devices. This brings together a range of concepts from basic physics to information processing in its most generalized form. Optical systems based on content-addressable memory processing, associative processing, Givens rotations, and hyperbolic rotations are being analyzed starting from basic physical principles and extending through experimental systems performance.

RESEARCH ACCOMPLISHMENTS:

- *Matrix Triangularization Using Givens Rotation Devices*

  We have previously shown that the elementary rotation matrix operation (and thus the Givens rotation) may be implemented in an optical micro-chip (integrated optics) form using an interdigitated-electrode-induced electro-optic grating at an intersection of dielectric waveguides. With an array of these devices, matrix triangularization may be performed. A specific design of an array of these orthogonal transformation devices together with the needed interconnecting waveguides for the purpose of performing matrix triangularization has now been presented. A central problem in computing is that of solving sets of linear equations. With matrix triangularization integrated optical processor presented, such systems of equations may be solved. Applications include: remote sensing, ultra-high resolution image processing, control of communication networks, air traffic control, synthetic aperture radar imaging, missile guidance, defense early warning systems, and simulation problems such as aerodynamic modeling and weather prediction. This research was published as an invited paper in *Computer*.

- *Antireflection Grating Surfaces: Experimental Verification*

  A systematic procedure using the effective index method and impedance matching has been developed by us [Appl. Optics 26, 3123 (1987)] for the design of antireflection high spatial-frequency rectangular-groove gratings on lossy materials including high conductivity metals. The design procedure, in turn, can be used as a starting point to design antireflection metallic gratings with lower spatial-frequencies using rigorous coupled-wave analysis. These lower spatial-frequency gratings have the advantage of being easier to fabricate. A particular antireflection gold grating design (having a period of $1.0\mu m$, a filling factor of 50% , and a groove depth of $147.5nm$ for use at a freespace wavelength of $500nm$, normal incidence, and polarization parallel to the grooves) was fabricated and its diffraction characteristics experimentally measured. The grating indeed showed very nearly zero specular reflection in the blue region of the spectrum. Unlike previously reported antireflection "anomalies," the effect is broadband occurring over a broad range of wavelengths and angles of incidence, and for both orthogonal polarizations. This work clearly shows that the systematic design of zero specular reflection grating surfaces is possible. Applications include construction of polarization selective mirrors and windows for high power lasers, higher efficiency photodetectors and solar cells, optical elements such as wave plates and polarizers, and airframes that are antireflecting at microwave frequencies. These experimental results will appear in the September 1, 1988 issue of *Applied Optics.*

- *Silicon VLSI-Compatible Ferroelectric Liquid Crystal Light Modulators*

  The development of optically interconnected VLSI and wafer-scale systems has a prerequisite the existence of a light modulator technology compatible with logic circuit technology that will enable the unconstrained placement of a large number of logic-driven light sources on a die or wafer. Integrated lasers, multiple quantum well electro-absorption modulators, and organic electro-optic materials exhibit high speed but are insufficiently mature to permit system prototyping, especially in silicon. Ferroelectric liquid crystals (FLC's) possess low switching energies and driving voltages in the surface stabilized cell configuration and are therefore well-matched to the output characteristics of silicon CMOS logic gates. Rapid development of faster materials is underway, with switching times of $3\mu sec$ at $15V/\mu m$ available now. We have developed a procedure that incorporates fabrication of most components of a reflective surface-stabilized FLC light modulator cell into unmodified CMOS processing. The reflective electrode and $1\mu m$ - $1.5\mu m$ thick spacer can be obtained by specifying features in the mask description of the die. Light sources can thus be placed in the same manner as transistors. Prototype 8×8 spatial light modulator arrays have been fabricated by us and exhibit contrast ratios of 40 to 1 which are much more than adequate for optical digital processing.

- *Electron Wave Optics in Semiconductors*

  Starting from fundamental principles, quantitative analogies between quantum mechanical electron waves in semiconductor materials and electromagnetic optical waves in dielectrics have been developed. This, in turn, suggests many new classes of electron wave optical devices such as narrow-band superlattice interference filters. Phase effects associated with an electron wave are incorporated using an "electron wave phase refractive index" that is proportional to the square root of the product of the electron effective mass and the electron kinetic energy. It has been shown by us that the amplitude of an electron wave is analogous to the electric field of a TE polarized electromagnetic wave (or to the magnetic field of a TM polarized electromagnetic wave) in a dielectric. Amplitude effects associated with an electron wave are incorporated using an "electron wave amplitude refractive index" that is proportional to the square root of the ratio of the kinetic energy to the effective mass. A simple expression for the critical angle for total internal reflection of an electron wave has been developed. By analogy to the electromagnetic optical case, the total electron transmissivity and reflectivity of a semiconductor superlattice is presented. For illustration, an electron wave interference filter that is the counterpart of a multilayer quarter-wave stack thin film optical interference filter has been designed as a variable bandgap and variable thickness semiconductor superlattice. These results have been accepted for publication in the *Journal of Applied Physics.*

  It is clear that a wide variety of electron wave optical devices are possible using electron wave propagation above the barrier and that these devices can be designed by directly using existing optical designs and the analogies presented here. Possible devices include low pass filters, high pass filters, notch filters (narrow band and wide band), bandpass filters (narrow band and wide band), and impedance transformers (antireflection coatings), and high reflectance surfaces (dielectric mirrors). These filter devices can have Butterworth (maximally flat), Chebyshev, elliptic function, or other type of characteristics. Narrow band filters can be incorporated monolithically into transistor structures in order to increase their speed. Pumping a superlattice resonant cavity gives rise to the possibility of a coherent electron wave amplifier and/or emitter. These are all one-dimensional quantum well type devices. Two-dimensional and three-dimensional devices such as beamsplitters, cylindrical lenses, spherical lenses, and diffraction gratings ar also possible using quantum wire and quantum box structures. These devices could assist in the control freespace electron beams in fields such as electron spectroscopy, electron beam lithography, and electron diffraction analysis of crystals.

PUBLICATIONS:

1. T. K. Gaylord and A. Knoesen, "Passive Integrated Optical Anisotropy-Based Devices," *Journal of Modern Optics*, vol. 35, no. 6, pp. 925-946, 1988.

2. R. S. Weis and T. K. Gaylord, "Fabry-Perot/Šolc Filter with Distributed Bragg Reflectors: A Narrow-Band Electro-Optically Tunable Spectra Filter," *Journal of the Optical Society of America A*, vol. 5, pp. 1565-1570, September 1988.

3. N. F. Hartman and T. K. Gaylord, "Antireflection Gold Surface-Relief Gratings: Experimental Characteristics," *Applied Optics*, vol. 27, pp. 3738-3743, September 1988.

4. E. N. Glytsis and T. K. Gaylord, "Antireflection Surface Structure: Dielectric Layer(s) over a High Spatial-Frequency Surface-Relief Grating on a Lossy Substrate," *Applied Optics*, vol. 27, pp. 4288-4304, October 1988.

5. E. N. Glytsis and T. K. Gaylord, "Anisotropic Guided-Wave Diffraction by Interdigitated Electrode-Induced Phase Gratings," *Applied Optics*, vol. 27, pp. 5031-5050, December 1988.

6. T. K. Gaylord and K. F. Brennan, "Semiconductor Superlattice Electron Wave Interference Filters," *Appl. Phys. Lett.* vol. 53, pp. 2047-2049, November 1988.

7. T. A. Maldonado and T. K. Gaylord, "Electrooptic Effect Calculations: Simplified Procedure for Arbitrary Cases," *Applied Optics*, vol. 27, page 5051-5066, December 1988.

8. A. Knoesen, T. K. Gaylord and M. G. Moharam, "Hybrid Guided Modes in Uniaxial Dielectric Planar Waveguides," *Journal of Lightwave Technology*, vol. 6, no. 6, pp. 1083-1104, June 1988.

9. M. M. Mirsalehi, T. K. Gaylord, D. C. Fielder and C. C. Guest, "Comparison of Number Systems in Truth-Table Look-Up Processing: Eight-Bit Addition Example," submitted to *Applied Optics.*

10. R. S. Weis and T. K. Gaylord, "Magneto-Optic Multilayered Memory Structure with a Birefringent Superstrate: A Rigorous Analysis," submitted to *Applied Optics.*

11. T. K. Gaylord and K. F. Brennan, "Electron Wave Optics in Semiconductors," accepted for publication in *Journal of Applied Physics.*

12. T. K. Gaylord and K. F. Brennan, "Semiconductor Superlattice Electron Wave Interference Filters," submitted to *Applied Physics Letters.*

TECHNOLOGY TRANSFER:

Air Force: Rome Air Development Center
- Optical content-addressable memory processing (R. L. Kaminski)
- Data/knowledge base systems (R. Liuzzi)
- Digital Optical Computing Program (R. Michalak)

Army: U. S. Army Technology Base Investment Strategy Conference
- Invited seminar, "Optical Computing," Applied Physics Laboratory, Johns Hopkins University, Laurel, Maryland

Army: Materials Technology Laboratory, Watertown Arsenal
- Optical waveguide analysis (G. C. Vezzoli)
- Gallium arsenide waveguide characterization (G. C. Vezzoli)

Navy: Naval Weapons Center
- Grating design for beam combining (J. M. Elson)
- Analysis of surface-relief gratings (L. F. DeSandre)

Industry:

AT&T
Antireflection grating surfaces (via R. J. Kyle, Technology Transfer Office, Georgia Tech)

EG&G Solid State Products
Antireflection grating surfaces (via R. J. Kyle, Technology Transfer Office, Georgia Tech)

Honeywell Optoelectronics
Antireflection grating surfaces (via R. J. Kyle, Technology Transfer Office, Georgia Tech)

Hughes Research
Antireflection grating surfaces (T. D. Wise)
Diffractive head-up displays (G. Moss)

Grumman Corporation
Antireflection grating surfaces (T. Hilgeman)

Opticomp Corporation
Digital optical computer design (P. S. Guilfoyle)

Westinghouse
Birefringent filters (A. P. Goutzoulis)

PATENT APPLICATION:

T. K. Gaylord, E. N. Glytsis, M. G. Moharam and W. E. Baird, "Technique for producing antireflection grating surfaces on dielectrics, semiconductors, and metals," filed July 26, 1988. Georgia Tech invention number 953, attorney docket number 10733-034 and UTC number 10-87-020.

Work Unit Five

TITLE: Two-Dimensional Optical/Electronic Signal Processing

SENIOR PRINCIPAL INVESTIGATOR:

W. T. Rhodes, Professor

SCIENTIFIC PERSONNEL:

S. D. Goodman, Graduate Research Assistant (Ph.D. Candidate)
J. N. Hereford, Graduate Research Assistant (Ph.D. Candidate)
R. W. Stroud, Graduate Research Assistant (Ph.D. Candidate)
J. van der Gracht, Graduate Research Assistant (Ph.D. Candidate)

SCIENTIFIC OBJECTIVE:

The long term scientific objective of this research is to gain a good understanding of the capabilities and limitations of hybrid optical/electronic methods for high throughput processing of 2-D signal information and to develop new and widely applicable techniques based on such methods. Emphasis is placed on establishing the capabilities of systems that mate well with digital signal processing systems.

RESEARCH ACCOMPLISHMENTS:

Effort since 1 January 1988 has been concentrated in the following three areas:

- *Optical Morphological Transformations and Extensions*

  An invited paper (cover article) on nonlinear image filtering using optical morphological transformations and time-sequential threshold decompositon was published in the April 1988 issue of *Optical Engineering*. During the summer we constructed an improved version of our basic experimental setup suitable for more flexible experiments. Using it we demonstrated a novel modification of the basic morphological transformations method using a gray-scale kernel rather than the normal binary kernel. The work is dignificant because it allows certain impulsive noise removal operations to be performed in half as many steps. A manuscript is near completion and ready to be submitted for publication. We expect to do further work in evaluating the effects of soft nonlinearities on the processing operations. In addition, we will investigate application of the method to human-vision-based edge-detection schemes.

- *Partially Coherent Optical Systems for Image Enhancement*

  We have now written and tested most of the software for simulating partially coherent optical imaging systems. In this work we have the important goal of minimizing the computational effort, which is historically tremendous for such simulations. (Full 2-D simulations are rarely carried out for distributions greater than 64×64.) The software assumes that object, pupil, and source distributions are separable in x and y, consistent with our belief that major computational savings will result from outer product expansions of these distributions using truncated singular value decompositions representations. Calculations of computational complexity indicate that dramatic savings in processing effort occur if the SVD expansions can be truncated at roughly the 10%-of-full-rank level. A manuscript describing sampling conditions that apply to partially coherent imaging operations has been submitted to *Applied Optics.*

- *Three-Dimensional Image Processing*

  Toward the end of the last report period we had determined under what conditions the volumetric imaging operation performed by a confocal, telecentric imaging system could be described by a simple 3-D convolution integral. Recently we have shown that virtually any standard imaging system can be modeled using a convolution formulation so long as appropriate geometrical distortions are introduced in the object and image spaces. we have worked out what we think is the most compact formulation of this method of 3-D imaging system analysis and are preparing material for publication. We are now using this model in connection with general 3-D optical image restoration investigations. One problem being investigated is that of determining, from a number of measurements in image-space planes, what the configuration of a surface-type object distribution is. One method based on projection-based concepts appears to be particularly promising.

- *New Methods for Exploiting Spatial Light Modulators*

  This past summer we began looking at new ways of using spatial light modulators that overcome some of the typical deficiencies connected with such devices. One student has begun a detailed study of the errors that result in image correlation operations when SLM's are used with finely-quantized phase but only coarsely-quantized magnitude transmittance values. Initial results suggest that currently-available SLM's used in this mode can out-perform the binary-phase and phase-only SLM's that have been reported as being so successful in coherent optical correlators. A manuscript on the subject, nearly completed now, will be submitted soon to a rapid-publication journal. In another study we are investigating ways of using binary spatial light modulators (which are currently available with good optical quality) in time-integration modes, greatly increasing the versatility of these devices for certain classes of optical signal processing operations.

- *Dimensional Mappings in Optical Signal Processing*

  A paper in this area, "Generalization of the Falling Raster-Folded Spectrum Relationship," by David N. Sitter and William T. Rhodes, was accepted for publication in *Journal of the Optical Soceity of America A*. This paper reports on work completed last summer describing a new way of formatting one-dimensional signal information for processing in a two-dimensional optical system. The relationship these formatting schemes have to different fast Fourier transform (FFT) algorithms is also discussed.

In addition to these three major investigations, we are looking at new ways of using spatial light modulators that overcome some of the typical deficiencies connected with such devices. One student is looking at the errors that result in image processing operations when SLM's are used with finely-quantized phase but only coarsely-quantized magnitude transmittance values. In another study we are investigating ways of using binary spatial light modulators (which are now available commercially with good optical quality) in time-integration modes, greatly increasing the versatility of these devices for certain classes of optical signal processing operations.

PUBLICATIONS:

Journal Articles

1. S. D. Goodman and W. T. Rhodes, "Symbolic Substitution Applications to Image Processing," *Applied Optics*, vol. 27, no. 9, pp. 1708-1714, May 1988.

2. J. M. Hereford and W. T. Rhodes, "Nonlinear Optical Image Filtering by Time-Sequential Threshold Decomposition," *Optical Engineering*, vol. 27, no. 4, pp. 274-279, April 1988.

3. D. N. Sitter, Jr. and W. T. Rhodes, "Generalization of the Falling Raster-Folded Spectrum Relationship," submitted to *Applied Optics.*

4. J. van der Gracht and W. T.Rhodes, "Source Sampling for Incoherent Imaging and Spatial Filtering," submitted to *Applied Optics.*

Work Unit Six

TITLE: Electromagnetic Measurements in the Time and Frequency Domains

SENIOR PRINCIPAL INVESTIGATORS:

G. S. Smith, Professor

SCIENTIFIC PERSONNEL:

W.R. Scott, Jr., Assistant Professor
M. Gouker, Graduate Research Assistant (Ph.D. Candidate)
J.G. Maloney, Graduate Research Assistant (Ph.D. Candidate)
G.P. Zhou, Graduate Research Assistant (Ph.D. Candidate)

SCIENTIFIC OBJECTIVE:

The broad objective of this research is to develop new methodology for making electromagnetic measurements directly in the time domain or over a wide bandwidth in the frequency domain. This research includes the development of the theoretical analyses necessary to support the measurement techniques. One aspect of the research is the systematic study of radiating structures placed near or embedded in material bodies. In a practical situation, the radiator might serve as a diagnostic tool for determining the geometry, composition or electrical constitutive parameters of the body.

RESEARCH ACCOMPLISHMENTS:

- *Materials for Electromagnetic Scale Models*

  In this research, simple emulsions were examined as materials with adjustable electrical constitutive parameters. These emulsions are mixtures of oil, saline solution, and a suitable stabilizing agent (emulsifier). Since the relative permittivities of oil and water are around two and eighty, respectively, a large range of permittivity can be obtained for the emulsions. The conductivity of the emulsions can be adjusted by changing the normality of the saline solution. A series of oil-in-water emulsions (oil droplets in water), suitable for use in scale models, was developed; this includes the selection of an appropriate emulsifier. The electrical constitutive parameters of these emulsions are adjustable over wide ranges and are predictable from a simple formula.

  The emulsions should be particularly useful for representing geophysical materials in models for buried antennas, subsurface radars, etc.

- *A Scale Model for Studying Ground Penetrating Radars*

  A scale model was developed for experimentally studying ground penetrating radars. The model is one-third full size and is used with transient signals that have significant frequency content within the range 150 MHz to 1.5 GHz. A unique feature is that the earth in the model is represented by an emulsion, which is a mixture of mineral oil, saline solution, and a stabilizing agent (described above). This emulsion is a scale model for red-clay earth; it matches the electrical parameters of the clay, including the dispersion in the conductivity, over a ten-to-one frequency range.

  Typical results measured with the model include the pattern for the electric field transmitted by the radar into the earth and the radar signatures for pipes of various composition buried in the earth.

  The model permits easy experimental comparison of different configurations for a radar and the eventual optimization of the radar for a particular application.

- *Pulse Excited Antenna*

  Radars that use base band pulses, such as ground penetrating radars, require antennas that can radiate and receive temporally short, wide bandwidth pulses. These antennas have traditionally been analyzed using approximate methods, such as transmission line models or assumed current/aperture distributions. The antennas are generally electrically large (many wavelengths long) at the highest frequencies contained in the pulse. Thus conventional frequency-domain numerical techniques, such as the method of moments, coupled with a fast Fourier transform are not efficient for analyzing these antennas.

  We have initiated a study of these antennas using the finite-difference time-domain technique. So far, the technique has been used to study pulse excited cylindrical and conical monopoles. Calculated results for these antennas are in good agreement with measurements.

- *Millimeter Wave Substrate Mounted Antennas*

  The applications discussed in the literature for substrate mounted antennas are primarily millimeter wave radars and imaging systems. We are studying these antennas for a different application - free space energy transfer at millimeter wavelengths. For this application, the antenna is combined with a rectifying element (diode) and referred to as a "rectenna." This research is a coordinated effort between the School of Electrical Engineering and the Georgia Tech Research Institute (GTRI). NASA is currently providing low level support to GTRI for research on millimeter wave rectennas. The JSEP effort complements this research by including personnel from the School of Electrical Engineering.

  Substrate mounted dipoles with bolometer detectors have been constructed and their field patterns measured at the frequency 230 GHz. The behavior of these

antennas is generally in agreement with what one would expect from theoretical considerations. However, some refinement in the experimental portion of the program is needed before more sophisticated antennas can be tested. Currently the evaporator that is used to deposit the bismuth bolometer detectors is being reworked, and the accuracy of the millimeter wave antenna range used for pattern measurements is being improved.

PUBLICATIONS:

Journal Articles:

1. G.S. Smith and W.R. Scott, Jr., "The Use of Emulsions to Represent Dielectric Materials in Electromagnetic Scale Models," accepted for publication in *IEEE Trans. Antennas and Propagation.*

2. G.S. Smith and W.R. Scott, Jr., "A Scale Model for Studying Ground Penetrating Radars," accepted for publication in *IEEE Trans., Geoscience, and Remote Sensing.*

3. W.R. Scott Jr., "A General Program for Plotting Three-Dimensional Antenna Patterns," submitted to *IEEE Trans. Antennas and Propagation.*

4. J.G. Maloney, G.S. Smith, and W.R. Scott, Jr., "Accurate Computation of the Radiation from Simple Antennas Using the Finite-Difference Time-Domain Method," submitted to *IEEE Trans. Antennas and Propagation.*

Papers in Conference Proceedings:

1. G.S. Smith and W.R. Scott, Jr., "Emulsions as Materials with Adjustable Dielectric Properties," 1988 International IEEE Antennas and Propagation Symposium, Syracuse, NY, June 1988.

TECHNOLOGY TRANSFER:

An invited seminar entitled "Overview of Buried Antennas" was presented at the U.S. Air Force Rome Air Development Center.

Work Unit Seven

TITLE: Automated Radiation Measurements for Near- and Far-Field Transformations

SENIOR PRINCIPAL INVESTIGATOR:

E. B. Joy, Professor

SCIENTIFIC PERSONNEL:

R. E. Wilson, (Ph.D. Candidate)
Mike G. Guler, Graduate Research Assistant (Ph.D. Candidate)
Donald Black, Graduate Research Assistant (Ph.D. Candidate)
Angela R. Dominy, Graduate Research Assistant (Ph.D. Candidate)
Joe Epple, Graduate Research Assistant (Ph.D. Candidate)
Ashley L. Slappy (M.S. Candidate)
John R. Dubberley (Undergraduate)
Scott C. Waid (Undergraduate)

SCIENTIFIC OBJECTIVE:

The long term objective of this research is to understand the near-field and far-field coupling between antennas in the presence of scatterers. Special emphasis is placed on determination of limits of accuracy in the measurement of the fields radiated or scattered by an antenna-under-test by a second antenna and to develop techniques and computer algorithms for compensation of such measurements due to known geometrical or electromagnetic anomalies.

Three application areas are pursued: a) antenna measurements, where the effects of scatterers are suppressed or compensated, b) scattering measurements, where the effects of scatterers are enhanced, and c) radome measurement, where the effects of the scatterer (the radome) are of equal importance to the antenna measurement.

RESEARCH ACCOMPLISHMENTS:

- *Radome Anomaly Detection Using Spherical Near-Field Measurement*

  A theory and technique have been developed, implemented and tested for the non-invasive, high accuracy determination of radome wall performance. The technique has a demonstrated spatial resolution of better than one-half wavelength. The technique involves the backward propagation of the measured spherical surface fields surrounding the radome. The fields are propagated to the surface of the radome and compared to the backward propagated fields made without the radome present. The difference between these two backward propagated fields shows the

transmission properties of the radome at each point of the radome wall. High accuracy and resolution have been demonstrated and could lead to an order of magnitude improvement in radome electromagnetic performance.

- *Shaped Serrated Diffraction Fence Theory and Design*

  Previous research conducted in the analysis of compact range performance and subsequent theory and technique for the design of flower-petal-shaped edge serrations has been applied to the theory and technique of far field range ground reflection reduction. Diffraction fences commonly used on far field antenna ranges to reduce ground reflections can be improved through the use of a flower-petal-shaped top edge serration. On the order of 10 dB improvement in far field ground reflection reduction is predicted in a computer simulation of such a serrated edge fence as compared to the common flat top fence.

PUBLICATIONS:

Books or Chapters in Books:

1. E. B. Joy, "Near Field RCS Measurement Ranges," Chapter 12, *Techniques of Radar Reflectivity Measurement*, N. C. Currie (Ed.), Artech House, 1989.

Journal Articles:

1. E. B. Joy, "Near-Field Range Qualification Methodology," *IEEE Transactions on Antennas and Propagation*, vol. 36, no. 6, June 1988, pp. 836-844.

2. E. B. Joy, "A Brief History of the Development of the Near-Field Measurement Technique at the Georgia Institute of Technology," *IEEE Transactions on Antennas and Propagation*, vol. 36, no. 6, June 1988, pp. 740-745. (Invited)

3. E. B. Joy, "Sampling Requirements for Spherical Surface Far-Field and Near-Field Measurements," (First) Antenna Measurements Article in *IEEE Antennas and Propagation Society Newsletter*, vol. 30, no. 6, December 1988. (Invited)

Conference Proceedings:

1. E. B. Joy and R. E. Wilson, "Low Side-Lobe Reflectors for Compact Ranges," *Proceedings of the 11th ESTEC Antenna Workshop on Antenna Measurements*, Gothenburg, Sweden, June 20-22, 1988, pp. 95-103.

2. E. B. Joy, M. G. Guler, R. E. Wilson, J. R. Dubberley, A. L. Slappy, S. C. Waid, and A. R. Dominy, "Near-Field Measurement of Radome Anomalies," *Proceedings of the Nineteenth Electromagnetic Window Symposium*, Atlanta, Georgia, September 7-9, 1988, pp. 137-145.

3. R. E. Wilson and E. B. Joy, "Shaped Serrated Diffraction Fence Tops for Improved Far-Field Range Performance," *Proceedings of the 1988 Antenna Measurement Techniques Association Meeting*, Atlanta, Georgia, September 12-16, 1988, pp. 12-19 through 12-23.

4. D. N. Black and E. B. Joy, "A Model for the Quiet Zone Effect of Gaps in Compact Range Reflectors," *Proceedings of the 1988 Antenna Measurement Techniques Association Meeting*, Atlanta, Georgia, September 12-16, 1988, pp. 9-15 through 9-20.

5. M. G. Guler, E. B. Joy, R. E. Wilson, J. R. Dubberley, A. L. Slappy, S. C. Waid and A. R. Dominy, "Spherical Backward Transform Applied to Radome Evaluation," *Proceedings of the 1988 Antenna Measurement Techniques Association Meeting*, Atlanta, Georgia, September 12-16, 1988, pp. 3-27 through 3-30.

6. E. B. Joy, "Electrical Characteristics of Building Materials," *Proceedings of the Second Annual Radome Materials Program Conference*, Columbus, Ohio, September 20-21, 1988, pp. 4-1 through 4-28.

PATENTS:

1. E. B. Joy, "Low Sidelobe Reflectors," filed September 1988. This patent is for the flower-shaped-edge serration that was found to significantly improve the performance of compact antenna ranges and low sidelobe level reflector antennas. This work was supported by JSEP and the US Army Electronic Proving Ground.

TECHNOLOGY TRANSFER:

1. U. S. Army Electronic Proving Ground, Fort Huachuca, Arizona: The technology for the design of improved compact ranges is being implemented in the design and construction of a large, 7 million dollar, outdoor compact range at Fort Huachuca.

2. U. S. Navy Aegis Near-Field Range at Westinghouse in Baltimore, Maryland: Many of the JSEP sponsored research results are being implemented in the design and construction of this multi-million dollar facility. This facility will be the most accurate antenna measurement facility in the world.

Work Unit Eight

TITLE: Angular Spectrum Analysis for Non-Uniform Arrays

SENIOR PRINCIPAL INVESTIGATOR:

James H. McClellan, Professor

SCIENTIFIC PERSONNEL:

D. Lee, Graduate Research Assistant (Ph.D. Candidate)
K. Blanton, (Ph.D. Candidate)

SCIENTIFIC OBJECTIVE:

Many widely used algorithms for angle-of-arrival (AoA) estimation are restricted to array configurations where the sensors are equally spaced. This is especially true of methods based on signal modeling. A primary objective of this research activity is to develop new AoA techniques that are not restricted to uniform grids. Another is to derive array configurations that are well matched to the particular AoA technique being used. In the long run, we plan to extend these methods to the two-dimensional case.

RESEARCH ACCOMPLISHMENTS:

- *Signal Modeling over Non-Uniform Grids*

  We have succeeded in extending the well-known Steiglitz-McBride technique for exponential modeling to the case where the data samples lie on a non-uniform subset of a uniform grid. The new algorithm is iterative in nature and alternates between two phases: modeling and interpolation. The modeling phase attempts to find the best pole-zero parameters; the interpolation phase, to fill in the missing data. Although derived from a very different point of view, this algorithm turns out to be remarkably similar to the EM (expectation-maximization) algorithm, and others that compute the solution in a two step manner.

  Present work on this particular algorithm is being directed at analyzing the performance of this technique and comparing it to other methods that can also cope with the non-uniform sensor geometry. In addition, a general description of this class of algorithms has been developed to explain their similarities and differences.

  Future work will investigate different strategies for interpolation, and the extension of this two-phase strategy to higher dimensions.

- *Minimum Redundancy Non-Uniform Arrays*

  The objective of this work is to create algorithms for synthesizing non-uniform arrays that will perform well with AoA methods that are based on inter-sensor correlation measurements (e.g., maximum entropy, MUSIC, etc.) One way to attack the problem is to design the array to have the minimum number of sensors to generate the needed correlations (i.e., minimum redundancy). This approach is basically an exercise in combinatorics, because the algorithms must search over many possibilities. For large arrays, or 2-D arrays, this is prohibitive. Some approximate bounds on the redundancy are known, but there are no efficient ways to generate solutions that meet the bounds. Work is being directed at improving the bounds and deriving algorithms that will produce large arrays or 2-D arrays that approach the bounds.